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Binary supermassive black holes driving the nuclear activity in galaxies

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Abstract. Nuclear activity in galaxies is closely connected to galactic mergers and supermassive black holes (SMBH), which should lead to formation of binary black holes (BBH) in the center of mass of the galaxies merged. The magnitude of the nuclear activity can be connected to the evolution of a BBH, accounting for the $M_{\rm bh}$–$\sigma_\star$ and $M_{\rm bh}$–$M_{\rm bulge}$ relations and predicts correctly the relative fractions of different types of active galactic nuclei (AGN). This scheme explains also the connection between the galactic type and the strength of the nuclear activity, showing that most powerful, quasar-type AGN result from mergers with small mass ratios, while weaker, Seyfert-type activity is produced in unequal mergers. The scheme explains also the observed lack of galaxies with two active nuclei, which is attributed to effective early disruption of accretion disks around the secondary companion in BBH systems with masses of the primary smaller than $\sim 10^{10}$ solar masses.

Key words. galaxies: active — galaxies: evolution

1. Introduction

Nuclear activity in galaxies believed to result from accretion onto SMBH is closely connected to galactic mergers leading to formation of BBH (Begelman et al. 1980; Roos 1981) in the center of mass of postmerger galaxies. Timescales of dynamic evolution of a BBH can much longer than the activity phase in galactic nuclei (Merritt & Milosavljević 2005), hence properties of active galactic nuclei (AGN) should be related to the actual evolutionary stage of the BBH (Haehnelt & Kauffmann 2002; Lobanov 2007). Details of this relation are not known, and detections of secondary black holes in galaxies are seldom (Komossa et al. 2003). An analytical model (Lobanov 2007) is described here that can explain this fact and connect the nuclear activity with evolution of pairs of SMBH in post-merger galaxies. The model relates three basic components of a post-merger galaxy: a pair of SMBH, accretion disks around them, and the central stellar cluster. This description is used to calculate three basic properties of evolving pairs of SMBH: 1) separation at which accretion disks are destroyed around the secondary and primary SMBH, effectively quenching the nuclear activity, 2) conditions for a circumbinary disk to exist, and 3) AGN luminosity as a function of the evolutionary stage of the BBH.

The model predicts that the secondary black hole is likely to lose its accretion disk even before the two black holes form a gravitationally bound system, for all mergers with the

Send offprint requests to: A.P. Lobanov mass of the primary smaller than $\sim 10^{10}\,M_\odot$. This explains the lack of detections of the secondary SMBH in post-merger galaxies. Some of these elusive secondaries may be found among the ultra-luminous X-ray sources (ULX), in which case their luminosity should correlate with the distance to the centers of their host galaxies. Evidence for such a correlation is presented.

2. BBH evolution and the nuclear activity in galaxies

Evolution of a BBH formed in the course of a galactic merger has been studied extensively, both analytically (cf. Begelman et al. 1980; Roos 1981; Merritt & Milosavljević 2005) and with numerical simulations (cf. Haehnelt & Kauffmann 2002; Di Matteo et al. 2003; Mayer et al. 2008). However, it has been difficult to establish a quantitative connection between the BBH evolution and manifestations of the nuclear activity, while there is a number of papers in which a quantitative assessment of this connection has been made(cf. Dokuchaev 1991; Di Matteo et al. 2003). A recent analytical model (Lobanov 2007) describes the evolution of the AGN power as a function of the separation and mass ratio in a BBH system, providing a benchmark for studying the connection between BBH and AGN.

The main constituents of the model are: 1) binary system of supermassive black holes, 2) accretion disk, 3) central stellar bulge. The BBH is described by the masses M_1, M_2 ($M_1 \geq M_2$) of the two black hole and their separation r. The evolution of the BBH is described in terms of *reduced mass*, $\tilde{M}$, and *reduced separation*, $\tilde{r}$ of the binary. The reduced mass is defined as $\tilde{M} = 2\,M_2\,/\,M_{12}$. This definition implies $\tilde{M} = 0$ for $M_2 = 0$ and $\tilde{M} = 1$ for $M_2 = M_1$. If $q = M_2\,/\,M_1$ is the mass ratio in the system, then $\tilde{M} = 2\,q\,/(1+q)$. The reduced separation is given by $\tilde{r} = r\,/\,(r + r_\mathrm{c})$, where r_c is the separation at which the two black holes become gravitationally bound (this happens at $\tilde{r} = 1/2$). Binary systems have $\tilde{r} \leq 1/2$, while unbound pairs of SBH have $\tilde{r} > 1/2$.

The model predicts separations at which the accretion disk is destroyed around the secondary and primary black holes, as well as a separation at which a circumbinary disk may exist. Denoting $\epsilon_1 = M_1/M_\mathrm{eq}$, the disk disruption distances are

$$\tilde{r}_{d1} = \left(1 + \frac{\epsilon_1}{\tilde{M}^2(2-\tilde{M})}\right)^{-1} \qquad (1)$$

and

$$\tilde{r}_{d2} = \left(1 + \frac{\epsilon_1}{(2-\tilde{M})^3}\right)^{-1} \qquad (2)$$

for the primary and secondary black hole, respectively. A circumbinary disk can exist at orbital separations smaller than $\sim G\,M_1 \rho_\mathrm{out}^{1/2} c^{-2}$.

This description implies a critical mass $M_\mathrm{eq} = 1.86 \times 10^7\,M_\odot\,\phi^2\,\rho_\mathrm{out}/R_\mathrm{g}$, where ρ_out is the outer radius of the accretion disk, R_g is the gravitational radius of the black hole, and ϕ is the solid angle into which an outflow from the nucleus is directed. A binary system with two black holes of a mass M_eq will undergo disk destruction at the time of gravitational binding (at $\tilde{r}_\mathrm{d} = \tilde{r}_\mathrm{c} = 1/2$. In systems with $M_1 < M_\mathrm{eq}$ the destruction of accretion disk around the secondary will occur before the formation of a gravitationally bound system. For typical values of $\rho_\mathrm{out}/R_\mathrm{g} \approx 10^4$ and $\phi = 0.1$–0.3, M_eq reaches 10^9–$10^{10}\,M_\odot$. It implies that most of active galaxies formed by galactic mergers should undergo destruction of the disk around the secondary BH before or during the formation of a gravitationally bound systems. Since masses of the nuclear black holes in galaxies rarely exceed $10^{10}\,M_\odot$, this offers a natural explanation for the observed lack of active galaxies with double nuclei, since it predicts that *in most galaxies with binary black hole systems, the secondary companion will be inactive*.

The peak magnitude of the nuclear activity in a galaxy hosting a binary black hole system can also be connected with the reduced mass and orbital separation of the two black holes. Assuming that the accretion rate increases proportionally to the tidal forces acting on stars and gas on scales comparable to the accretion radius, $2\,G\,M_{\rm bh}/\sigma_\star^2$, the peak luminosity from an AGN can be crudely estimated from

$$L_{\rm peak} = L_0 \left(1 + \frac{\tilde{M}}{2-\tilde{M}}\frac{\tilde{M}}{\tilde{r}^2}\right) \tag{3}$$

where L_0 is the "unit" luminosity of a typical single, inactive galactic nuclei.

3. Observational evidence

The peak luminosity increases rapidly with increasing $\tilde{M}$ and decreasing $\tilde{r}$, and it reaches $L_{\rm peak} = 1000\,L_0$ for an equal mass binary SBH at $r \approx 0.03\,r_{\rm c}$. If galaxies are distributed homogeneously in the $\tilde{M}$–$\tilde{r}$ domain, then about 70% of all galaxies would be classified as inactive, while the Seyfert-type of galaxies, with $L_{\rm peak} =$ 10–100 L_0, would constitute 15% of the galaxy population, and the most powerful AGN, with $L_{\rm peak} > 100\,L_0$, would take the remaining 10%. These figures come close to the observed distribution of galaxies along these galactic types. This scheme implies that the most powerful AGN with $L_{\rm peak} > 1000\,L_0$ should be found in binary SMBH with nearly equal masses of the primary and secondary black holes. Binary SMBH with smaller secondary companions should produce (at the peak of their nuclear activity) weaker, Seyfert-type AGN. Evidence exists in the recent works (Laine et al. 2003; Letawe et al. 2006) that the nuclear luminosity does indeed increase with the progression of the merger, but more systematic and detailed studies are required.

Another viable posibility for finding the elusive secondaries is to look among ultraluminous X-ray objects (ULX) detected in a number of galaxies, including in particular interacting and post-merger galaxies (Swartz et al. 2004). Although it is still a matter of debate whether these objects are indeed massive black holes or simply unusual X-ray binaries (Zampieri 2006), some indication that at least a fraction of the ULX objects may be represented by massive (secondary) black holes in post-merger galaxies comes from an analysis of the properties of off-nuclear X-ray sources detected in the Chandra deep field observations (Lehmer et al. 2006). Detected alsmost exclusively in late-type spirals and irregulars, these objects show a peculiar trend of decreasing X-ray luminosity with the distance to centers of their host galaxies (Fig. 1).

3.1. Ultraluminous X-ray sources

The BBH model can explain this trend by gradual stripping of outer layers the accretion disk around a secondary BH in a post-merger galaxy. In this case, the accretion disk luminosity of the secondary, L_2, can be computed from $L_2 = 2\pi \int F_\nu(r)\, r\, {\rm d}r$, where $F_\nu(r) \propto r^{-(5+3a_\nu)/4}$ is the radial distirbution of spectral intensity. The power index a_ν depends on the observing band. For the X-ray observations presented in Lehmer et al. (2006), this results in $a_\nu(0.5{-}2.0\,keV) = 7/2$, with $L_2(0.5{-}2.0\,keV) \propto r^{15/8}$ and $a_\nu(0.5{-}8.0\,keV) = 4$, with $L_2(0.5{-}8.0\,keV) \propto r^{9/4}$.

Fig. 1 shows fits to the observed luminosity trends at both bands. The fits are normalized to a $10^8 M_\odot$ black hole accreting at $10^{-5}\dot{M}_{\rm Edd}$. The fitted trends explain well the observed decrease of the X-ray luminosity, suggesting that these off-nuclear X-ray sources can indeed represent the population of secondary black holes, activity of which is gradually quenched during their approach towards the center of mass of their post-merger galactic hosts.

4. Discussion

Despite the existing evidence in favor of the BBH scenario, the connection between BBH systems and the nuclear activity in galaxies needs further and more systematic studies. The model described above can be tested effectively with high-resolution optical studies and data from large surveys that can be used to obtain estimates of the nuclear luminosities and black hole masses in active galaxies. The most challenging task is to assess the state of the putative binary, since the secondary black holes are very difficult to detect. For wide binaries, direct evidence may be sought in galaxies with double nuclei and off-nuclear compact sources, similar to those described in

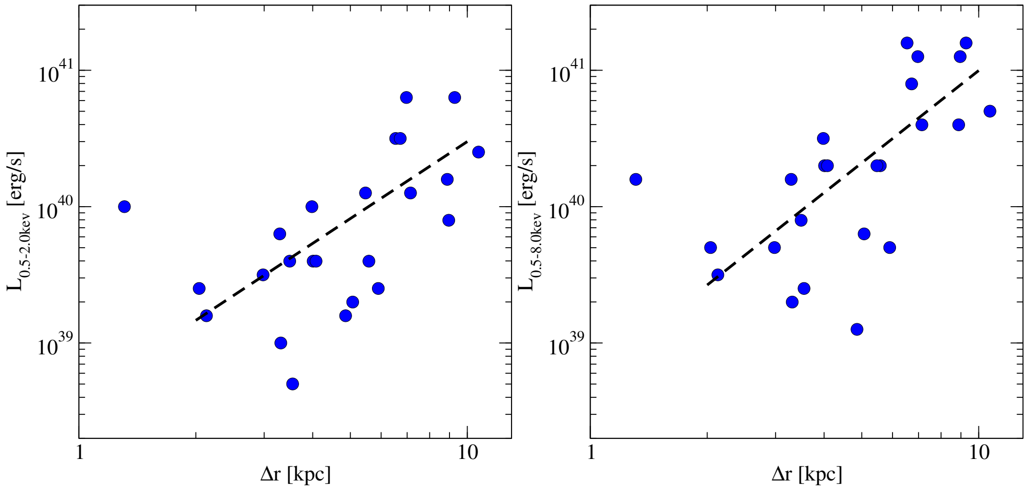

Fig. 1. Luminosities of off-nuclear X-ray sources detected in galaxies located in the Chandra Deep Field–North, Chandra Deep Field–South, and Extended Chandra Deep Field–South (**?**). Dashed lines show the luminosity trend predicted for secondary black holes in which accretion disks are being stripped in the course of the binary black hole evolution. The fits are normalized to a $10^8\,M_\odot$ black hole accreting at $10^{-5}\dot{M}_{\rm Edd}$.

Lehmer et al. (2006). Close binaries can probably be identified only indirectly, through periodic perturbations caused by the secondary companion. Other indicators, such as flattening of the galactic nuclear density profile due to BBH (Merritt & Milosavljević 2005), can also be considered. Once the binary separations have been estimated, it would be possible to populate the $\tilde{M}$–$\tilde{r}$ diagram (Lobanov 2007) and study whether different galactic and AGN types occupy distinctively different areas in the diagram.

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